Robotic System for Assisting Long-sleeved Shirt Dressing Using Two Manipulators with Different Roles*

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Abstract— **This study describes a long-sleeved shirt dressing support system, which mainly comprises two robotic manipulators, for people with half-body paralysis. To design a feasible support system, we obtain the opinions of occupational therapists and experimental psychologists. Based on their advices, we propose herein an appropriate dressing procedure that can be supported by robots. We also construct a robotic system to achieve the required assistance and implement some essential functions, including human pose recognition, end-effector trajectory generation for shirt sleeve manipulation, and arm motion support while dressing. Accordingly, we introduce admittance control for the arm motion support. This avoids the trouble of a person getting a large load while putting his/her arm through a shirt sleeve. We present the experimental results of an actual person wearing a long-sleeved shirt to show the usefulness of the proposed system.**

I. Introduction

In recent years, the declining birthrate, and aging population have resulted in a labor shortage in the nursing care industry. In addition, the accompanying increase in the number of nursing care refugees has become a serious problem, placing an increasing burden on persons requiring nursing care. One of the daily situations that require nursing care is the putting on and taking off of clothing. To do this by himself/herself is physically burdensome for a person who requires nursing care. This is especially difficult for those with paralysis or physical disabilities. Therefore, the use of automatic machines to provide dressing and undressing support is of great significance. It is expected to alleviate the need for manpower and help people with physical disabilities maintain self-esteem.

With the abovementioned background, the intelligent robotics field can contribute to alleviating this situation by creating a mechanism that allows automated machines to help persons with physical disabilities easily get dress. Several efforts exist in this regard [1–3]. Gao et al. [4] realized the task of putting on a sleeveless jacket while estimating the posture of a person's upper body in real time. Tamei et al. [5] expressed the phase relationship between a person and a clothing product in a low-dimensional state and successfully put a T-shirt through the head of a mannequin using reinforcement learning. Kapusta et al. [6] proposed a method using capacitance sensors attached to the robot's end-effector. These sensors were used to detect a human arm and realize the task of putting a shirt sleeve on that arm. Meanwhile, Yamazaki et al. [7] proposed image-based features using optical flow and was able to estimate the dressing situation. They also showed that it was possible to detect fabric snagging and recover from failure. One of the remaining issues with regard to this topic is the automatic generation of a failure recovery motion. Clegg et al. [8] proposed a method for representing physical disability on a simulator and used it for deep reinforcement learning. They succeeded in making a robot, which did not know the human's motion ability, but can assist in dressing. Erickson et al. [9] attached a multi-electrode capacitance sensor to a robot's end-effector to recognize human limbs in real time. Joshi et al. [10] used a dual-armed robot to assist in dressing using imitation learning from a human demonstration. The arm part was recognized by the dual-manipulation platform, while the body part was recognized by the Bayesian Gaussian process latent variable model (BGPLVM). Zhang et al. [11] proposed a personalized dressing assistance method based on hierarchical multitasking control and upper body motion modeling. Zhang et al. [12] also proposed a method that combines grasp point prediction using depth images, grasp posture calculation, and collision avoidance between robot and clothing. Koganti et al. [13] used the BGPLVM to study a dressing motion and obtained a dressing trajectory more efficiently than learning in joint space. Meanwhile, Li et al. [14] formulated a mechanical model of the human–robot interaction using a Gaussian process and realized a dressing aid that guarantees safety. Based on the formulated dynamical model, they generated a dressing trajectory that avoids contact or results in a safe contact. By the way, the authors also constructed a dressing system assuming a person with half-body paralysis [15]. This system used a hybrid control of position and force to put the paralyzed side arm through a shirt sleeve.

The abovementioned studies on dressing support assumed that an assisted person does not move much while dressing. Furthermore, it was not assumed that the robot moves the person actively. If a system consists of a robot that supports clothing operation and moves the person's body to facilitate dressing, that person may be able to use the system appropriately to perform the difficult task of dressing while maintaining self-esteem. This support is expected to enhance self-efficacy [16] because one can wear clothes by him/herself with a comprehensive, but supplemental support from previous robot systems.

We propose herein a dressing support system that mainly consists of two robotic manipulators. One robotic manipulator is responsible for putting a shirt sleeve on one arm. The other is responsible for assisting in moving the arm to a pose suitable for dressing. One system application is to help people with physical disabilities and those who need time to dress by themselves. To design this feasible robotic support system, we

* This work was partially supported by JST [Moonshot R&D][Grant Number JPMJMS2034] and KAKENHI.

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obtained the opinions of occupational therapists and experimental psychologists. Based on their advices, we created an appropriate dressing procedure suitable for robotic assistance and set up a robotic system with necessary recognition and motion generation functions. We confirm the effectiveness of the proposed system through actual dressing experiments.

The remainder of this paper is organized as follows: Section II explains our problem setting and approach; Section III explains our robot system and its required functions in detail; Section IV presents the experimental results; and Section V concludes this study.

II. Problem Setting and Approach

A. Concept of Wearing Assistance

A non-handicapped person generally takes the following steps to put one arm through a shirt sleeve: 1) the collar is grasped with the other arm; 2) the fingertips of the arm are put into the sleeve; and 3) the entire upper body is moved appropriately to path the latter arm through the sleeves.

In this study, we target people who can wear clothes to some extent by themselves, but find it difficult to complete the process. People with half-body paralysis are included in this category (i.e., in this case, only one hand can manipulate clothes). Although the person can wear clothes by himself/herself, the task completion takes much time and physical hardship. This can reduce that person’s motivation to wear clothes and lead to them to rely on others for support. Our goal herein is to prevent such a demotivation. It is desirable to simplify clothes manipulation, such that the time required for wearing clothes can be shortened.

Wearing a long-sleeved shirt with a front opening requires several steps. The following efficient procedure is proposed for people with hemiplegia: (1) sit on a chair, and hang the paralyzed arm between both legs; (2) grasp the collar of the shirt near the sleeve hole with the healthy hand; (3) put the paralyzed hand in the sleeve and pull it up to the shoulder; (4) release the healthy hand and grab the clothes again from behind the shoulders; (5) bring the remaining sleeves to the healthy side, and let pass the arm through the sleeves; and (6) after adjusting the shirt position, fasten the buttons to finish.

The major obstacle in the abovementioned steps is faced when performing Step 3, which is passing the arm on the paralyzed side through the shirt sleeve. In this step, the cloth often gets caught in the paralyzed arm, requiring the frequent pulling up of the stuck cloth with the healthy hand. Robotic assistance can reduce this action and lead to the smooth wearing of clothes. We tried to make a motion assist on this step and designed a mechanism that supports the movement of pulling up the sleeve on the paralyzed side with the hand on the healthy side [15]. When using this system, however, the user must significantly twist his/her torso. Therefore, this assistance may not be sufficient for some people. To address this, we devised a support method that simplifies human movement while preserving independence.

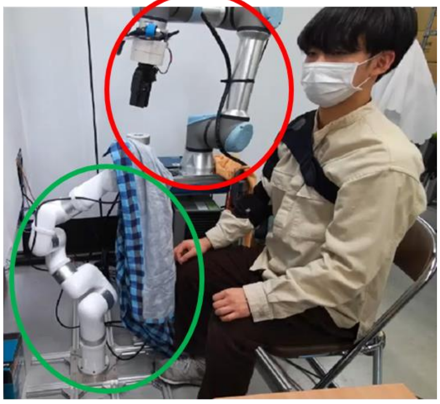


Fig. 1 Dressing assistant system. Two manipulator-type robots are used. One is for the dressing support. The other is for the arm motion support.

B. Dressing Assistance Procedure

Figure 1 shows the proposed dressing assistance system. The robotic arm circled in red is the dressing support robot (DSR) that performs the sleeve manipulation. The robotic arm circled in green is the arm support robot (ASR) that positions the person's arm in a posture suitable for dressing. Although we used multi-degree-of-freedom manipulators, fewer degrees of freedom may be acceptable, especially for the ASR.

With input from experimental psychology and occupational therapy experts, we developed the following procedure for dressing support (as a preliminary preparation, set the shirt sleeve on the tip of the ASR): 1) the person carries the paralyzed hand by the healthy hand and places it on the ASR tip; 2) the person grabs the shirt sleeve with the healthy hand and allows the DSR to grasp the sleeve; 3) the ASR moves its end-effector slightly such that the paralyzed arm and trunk of the person are in the appropriate position for dressing; and 4) the DSR begins to put the arm through a sleeve.

Based on this dressing method, the robot can replace the role of deformable object manipulation, which is troublesome work (e.g., snagging the cloth with the human elbow). Instead of fully automating the dressing process, the initiative remains with the human.

III. Dressing Assist System

A. Recognition and Motion Control Functions

The following recognition and motion control functions are required for the robot system to perform the proposed dressing procedure.

(a) A function to estimate the person pose: this is used to determine the trajectory of the robot's end-effector for putting one person’s arm through a sleeve using the DSR.

(b) A function to measure the force applied to the ASR and adjust the end-effector position: this is to prevent a large load from being applied to the person when the sleeve is caught on his/her paralyzed side during dressing.

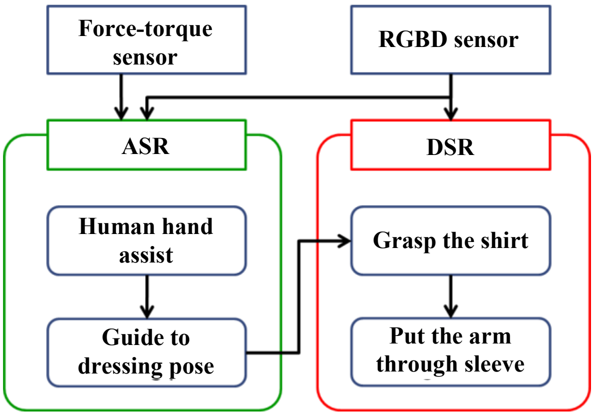


Fig.2 The relationships of sensor data and robot actions. Both manipulators (ASR and DSR) use sensor data and make motion for achieving each role.

For each of them, we respond as follows:

(a) An RGBD camera is installed in a position where the two robots and the subject can all be observed. We introduced a method to output a two-dimensional (2D) skeletal model of a person by taking a color image obtained from the camera as the input. The results are combined with a depth image to estimate the three-dimensional (3D) positions of the hand, elbow, and shoulder on the paralyzed side.

(b) Admittance control is introduced to the ASR during dressing by the DSR. This reduces the load on the person by moving the ASR in the force direction if the arm on the paralyzed side is pulled by the sleeve when snagging occurs.

B. *System Configuration*

The specific hardware configuration of the dressing support system will first be described. UR5e, which was manufactured by Universal Robots, Inc. and has 6 DoFs, was used for the DSR. A small and lightweight parallel jaw gripper of our own design was attached to the end of UR5e. xArm7, which was manufactured by UFACTORY, Inc., and has 7 DoFs, was used for the ASR. A six-axis force–torque sensor from UFACTORY was attached to the tip of xArm7. We do not have a particular reason for using two different robot arms, but xArm7 motion software is suitable for real-time control, which is one of the reasons we selected it for the ASR. Azure Kinect was used as the RGBD camera.

Figure 2 illustrates the relationships of the sensor data and the robot actions. The RGB and depth images and the force and torque data were used to make the motion of the two manipulators. Three main actions must be performed before starting the dressing. The DSR proceeds with the dressing action, while the ASR adjusts the position of the paralyzed hand. Section III-D describes this procedure in detail.

C. *Dressing Motion Generation*

As the first process, OpenPose [17] was used to estimate the human pose. OpenPose fits a whole-body bone model in a color image and outputs a list of nodes with 2D coordinates. The coordinates of the node of the shoulder, elbow, and wrist on the paralyzed side were obtained from the result. The depth values for each node point were then obtained from the depth image and combined for conversion to 3D coordinates.

The end-effector trajectory of the DSR for the sleeve dressing was determined based on these 3D coordinates. Each point was specifically translated vertically upward by a certain distance. The neighboring points were connected by a straight line. The resulting lines were set as the reference trajectory. In addition, it was necessary to devise a way to avoid collision with the person's arm considering the end-effector orientation. Therefore, the end-effector orientation was basically kept perpendicular to the trajectory line. Linear interpolation was used to make a smooth motion in the orientation when switching trajectory around the elbow. This procedure enabled the accommodation of various changes in body size.

D. *Admittance Control*

Admittance control is a commonly used robot control method in human–robot cooperation [18-20]. The robot's behavior can be controlled by changing the virtual stiffness, damping, and inertia parameters. Changing the inertia parameters makes it possible to generate a robot behavior that is in high affinity with the human motion.

In our dressing support method, the human arm was pulled by the sleeve during dressing with the help of the DSR. In this case, the human hand may slip off the ASR tip. Therefore, we tried to adjust the ASR tip position by admittance control to prevent the dressing work from collapsing. For simplicity, we applied the method proposed in [21] as a control method.

The basic formula of the admittance control is as follows:

$$\boldsymbol{V}_{\boldsymbol{ad}(t)} = \boldsymbol{F}_{(t)} e^{-\frac{C}{M}}, \tag{1}$$

where $\boldsymbol{F}$ is the force and torque vector (six elements) given by the force–torque sensor; M is the inertia parameter; and C is the damping parameter. These are fixed values empirically set to 5 kg and 10 N/m. The ASR output was calculated as follows:

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{-1} \boldsymbol{V}_{\boldsymbol{ad}(t)}, \tag{2}$$

where $\dot{\boldsymbol{q}}$ is the angular velocity vector of the ASR joints, and $\boldsymbol{J}^{-1}$ is the inverse Jacobi matrix. The control cycle was set to 10 [Hz]. Although this frame rate was not fast, we had no response performance problems in our experiments.

IV. Experiments

A. *Setup*

The proposed dressing support system consisted of two manipulators and two types of sensors. The system could be operated on a single desktop PC. ROS was used as the middleware. The calibration between the manipulators and the RGBD sensor is an important task after the hardware setup. This was performed using AR markers with the following procedure: 1) the AR markers were attached to each tip of the two manipulators; the markers were extracted from the color images obtained from the RGBD sensor; 2) from them, the 3D tip posture was calculated; 4) the AR_track_alver [22] package of ROS was used for this process; and 5) the calibration was

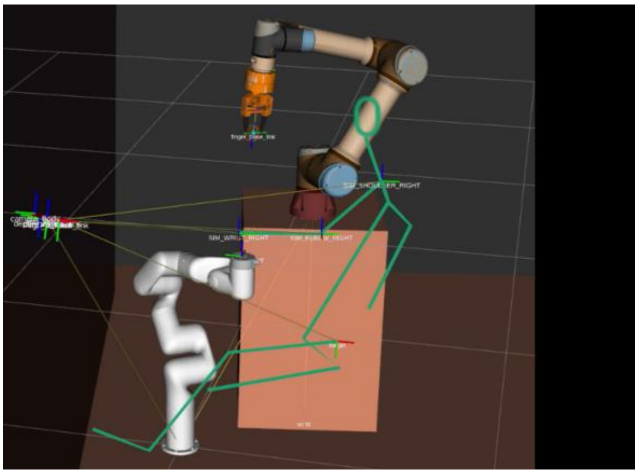


Fig.3 The virtualized experimental environment. The pose of RGBD sensor is shown by coordinates system in the leftmost part. The arrangement of ASR and DSR is obtained by calibration procedure. Human pose obtained by OpenPose is also shown by green line segments.

completed by back-calculating the manipulator's root pose from the obtained tip's pose, link lengths, and current joint angles.

Figure 3 displays a view of the results of the two manipulators and the sensor pose after calibration. The estimated human pose is also depicted by the green line segments. MoveIt was used to program the manipulator motion. RRT-connect [23] was selected as the motion planning method. However, the linear tracking of the end-effector was applied for the sleeve manipulation using the DSR.

B. *Experiments and Results*

We conducted an experiment, in which a subject wore a long-sleeved shirt using the constructed dressing support system. The subject in this experiment was an able-bodied person. However, we assumed the case of half-body paralysis here; thus, the subject's arm was placed in a state similar to that of a person with a disability by attaching a supporter around his shoulder.

First, as a preliminary preparation, the sleeve to be worn on the paralyzed side was gathered around the ASR's wrist. Next, the hand in the paralyzed side was placed on the ASR tip, and the shoulder part of the sleeve was held by the DSR. The DSR then moved in a trajectory along the arm. This procedure allowed the sleeve to gradually move from the ASR tip to the subject's arm, completing the dressing of the paralyzed side. Fig. 4 depicts this experiment. In (1) to (6), the paralyzed side was dressed with the assistance of the proposed system following the procedure described in Section II. In (7) and (8), the subject puts on the shirt on the healthy side by grasping the shirt from behind the shoulder with the hand of the healthy side. Dressing was completed with little active movement of the paralyzed arm side.

The dressing process took approximately 64 s. It took 4 s for the paralyzed hand to be placed on the ASR tip, 12 s for the ASR to move the subject to a suitable pose for dressing, 18 s for the subject to have the DSR grasp the shoulder part of the shirt, 18 s for the DSR to put his arm through the sleeve, and 12 s for the subject to put his arm through the sleeve on the non-handicapped side. There is room for a smoother human–robot corporation in some phases. In the future, this process should take less than 40 s.

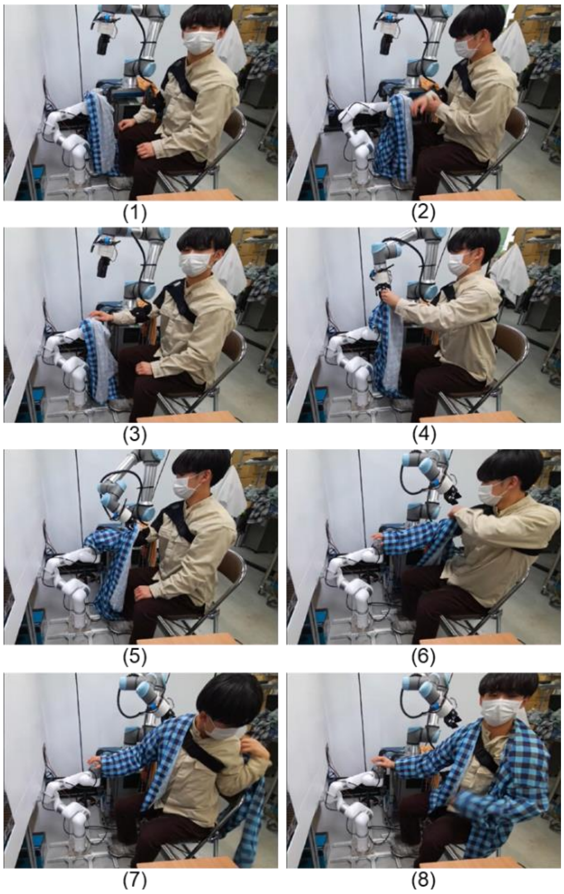


Fig.4 A sequence of shirt dressing. From (1) to (6), the subject uses the proposed dressing support system and pass the sleeve through the arm of paralyzed side. In (7) and (8), he wears the shirt on the healthy side.

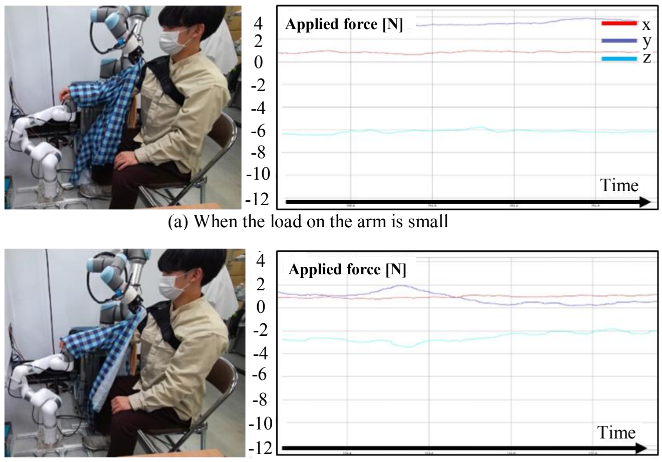
In case any particular trouble (e.g., snagging) occurs during the dressing operation, the output value of the ASR force sensor will be approximately 6 N in the vertical direction. When snagging occurs, the vertical force sometimes decreases to approximately 2 N. In other words, the arm on the paralyzed side is pulled by the sleeve, and the force to the ASR is reduced. Figure 5 shows snapshots of the force data while dressing. The xyz on the graph indicates the direction of the force applied to the force sensor. z is vertical to the palm of the person's hand placed on the ASR.

Approximately five experiments each with and without admittance control were performed for comparison. Dressing was completed in all trials in both cases. However, two major problems became apparent when admittance control was not used. First, a large burden was placed on the subject when the sleeve was caught on the subject's arms during the dressing process. Second, the paralyzed side moved in response when a strong snag occurred, causing the hand to almost fall off the ASR tip. When using admittance control, the ASR tip followed the subject's hand, even if it moves. Consequently, the subject's hand was prevented from falling from the ASR tip in advance.

V. CONCLUSION

In this study, we proposed a dressing support system comprising two manipulators, one RGBD camera, and one force–torque sensor. We considered people with half-body paralysis and proposed a novel procedure to help these people wear long-sleeved shirts. We achieved dressing support using the proposed system by implementing some essential functions, such as dressing motion generation and admittance control. We constructed an integrated robot system and confirmed the usefulness of the proposed system by dressing real persons who wear a fastening device. The proposed system can enable people with disabilities, even a person with severe hemiplegia, to dress themselves.

Our future work will include additional experiments for the quantitative evaluation of our system. As regards other development issues, we have to improve the way we cope with the snagging trouble and enhance the dressing support method. We should determine movement guidelines for the ASR to reduce the load caused by snagging. We should also build a DSR motion generation method that eliminates snagging.



(a) When the load on the arm is small

(b) When the load on the arm is large

Fig.5 Force sensor output while dressing. (a) shows the result without snagging, whereas (b) shows the case that snagging occurs. Light blue line shows the force value along vertical axis applied to the tip of ASR.

ACKNOWLEDGMENT

The authors grateful for the professional advice from Jun-ichi Yamamoto at Tokyo Metropolitan University and Makoto Suzuki at Tokyo Kasei University.

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